Environmental Aspects of Microwave Radiation

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Properties of Microwaves

Microwaves are electromagnetic waves which fall in the frequency range of approximately 30-300,000 MHz. The location of the microwave band in the electromagnetic spectrum is shown in Fig. 1. From the relation $\lambda = c/\nu$, (where λ is the wavelength of the radiation, c is the speed of light, and ν is the frequency) the range of the wavelength of the radiation in free space is determined to be 1000 centimeters-to 0.1 centimeter. Microwaves are often referred to as nonionizing radiation. Using the relationship, $E = h\nu$, (where h = Planck constant = 4.135 e.v.-sec) the energy per photon of the radiation can be calculated. For the microwave portion of the electromagnetic spectrum, the energy per photon ranges from 1.24×10^{-3} to 1.24×10^{-7} e.v. Since the ionization energy for atoms is of the order of 1 e.v., it can readily be seen that microwaves cannot ionize the atom. Therefore, any interaction between microwaves and biological material would be by a mechanism other than ionization.

The best understood mechanism of interaction of microwave radiation and biological material is the absorption of the microwave energy with a resulting increase in temperature of the biological specimen. The amount of energy absorbed depends on the electrical properties of the specimen. The two electrical properties of importance are the dielectric constant, a measure of the polarizability of the medium, and the conductivity, a measure of the ease in which electrically charged particles move through the medium. Since water has a relatively high dielectric constant and conductivity, the absorption of microwave energy is greater in biological materials

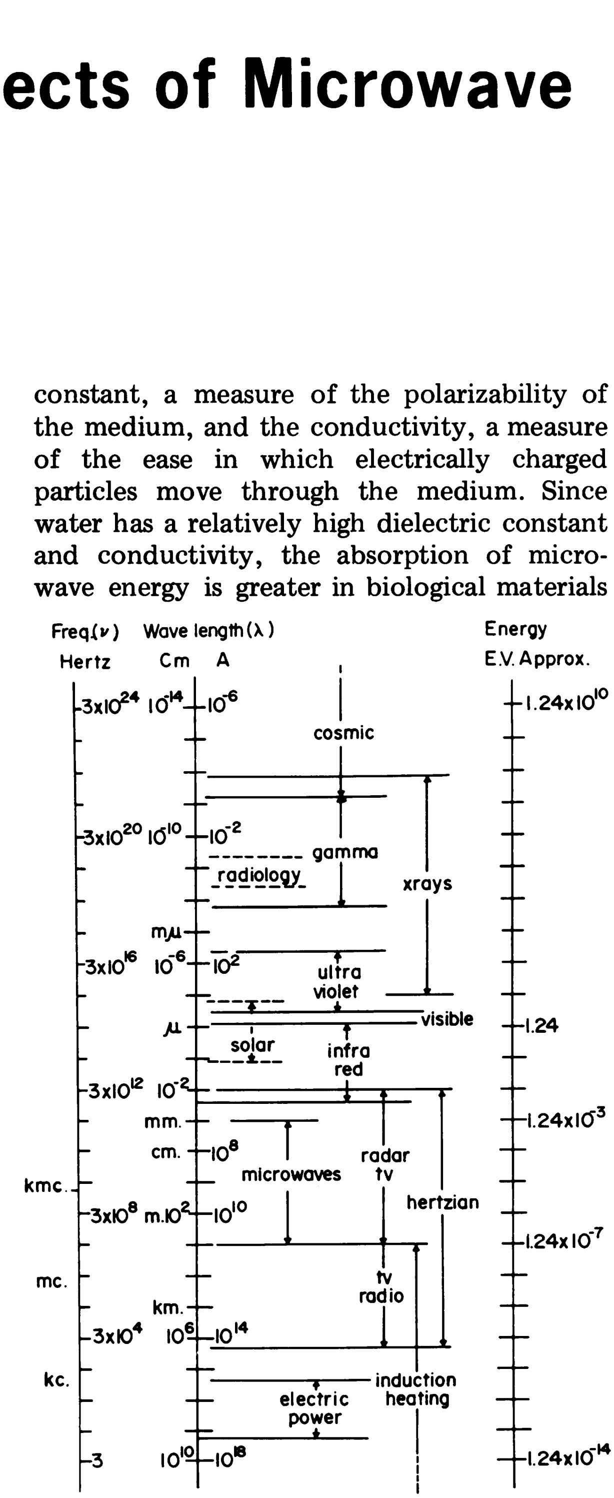

FIGURE 1. Electromagnetic spectrum.

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with high water content. The dielectric constant and conductivity of a specimen are also functions of frequency. Therefore, the amount of energy absorbed varies with the frequency of the radiation. Schwan (*1*) has presented the electrical properties of various body tissues for frequencies between 25 and 8500 MHz.

Another interaction mechanism, which has been experimentally observed and explained using simple physical principles (*2*), is the so-called field-force effects. These effects are concerned with forces which are imposed by alternating electrical fields on blood corpuscles, protein molecules or other biological particles. Applying the well-known principle that a system will tend to minimize its potential energy, one is able to describe the observed effects known as pearl-chain formation and the orientation of particles. These orientation effects occur only at power levels of approximately 500 mW/cm^2 and above, which are much higher than the accepted safe level of exposure.

The mechanisms of interaction described above have adequately explained some of the observed biological effects of microwave radiation. However, other biological effects, which have been observed at low energy level microwave fields are not explained by these mechanisms. Jaski (*3*) irradiated human subjects with low-power microwaves in the 300 to 600 MHz frequency range. Each subject reported an unusual feeling at one particular frequency between 380 and 500 MHz. The subjects agreed that the unusual feeling consisted of a "ringing" in the ears, a "pulsing" in the brain and a feeling of acute hostility. Frey (*4*) reports that some persons can "hear" radar-induced sound. Since some deaf people have reported "hearing" microwaves, Frey hypothesized that the microwaves affect the brain directly. He also suggests that the electric field of the microwave radiation could induce fields across the membrane of nerve cells of such magnitude that excitatory and inhibitory effects could occur in the nervous system. Kholodov (*5*) has measured brain wave alterations in rabbits exposed to power levels too low to cause gross heating. In order to insure that the radiation was acting directly on the brain rather than on the sensory systems, Kholodov destroyed the cochlea, severed the optic nerve, and sectioned the rhinencephalon; thereby omitting the sensations of hearing, sight, and smell. Still the altered brain waves occurred following irradiation. Since the nerve impulses are electrochemical phenomena and depend on the depolarization of the outer surface of the cell membrane with respect to the cytoplasm by the flow of sodium ions across the membrane, these effects could possibly be produced by the interaction of the electromagnetic field with this complex nerve conduction process. Other cellular functions, such as mitotic activity, depend also on membrane potential. Cone (*6*) experimentally determined that the changes in ionic concentration levels and distributions which accompany different membrane potential levels in somatic cells act to control DNA synthesis and hence mitosis. If the electromagnetic field of microwave radiation could be shown to interact with the cell membrane potential, this mechanism of interaction could explain some of the existing experimental results on cells and unicellular organisms. A great deal of additional research is needed to determine the potential hazards of low level microwave fields and to explain the mechanism of interaction of microwave radiation with complex biological systems.

Uses of Microwave Radiation

The microwave frequency band is divided into frequency subgroups and designated as shown in Table 1.

The Federal Communications Commission has designated the following frequencies for unlicensed use in industrial, scientific, and medical equipment (*7*):

13.56 MHz ± 6.78 KHz
27.12 MHz ± 160 KHz
40.67 MHz ± 20 KHz
915 MHz ± 25 MHz
2450 MHz ± 50 MHz

Table 1. Microwave Frequency Designation and Assigned Uses

Designation	Wavelength by Decades in CM	Frequencies in Multiples of Hertz	Some Assigned Uses
Very high frequencies (VHF)	10^3 to 10^2	30 MHz to 300 MHz	FM radio and television
Ultra high frequencies (UHF)	10^2 to 10	300 MHz to 3 GHz	Microwave ovens, radar, and some diathermy
Super high frequencies (SHF)	10 to 1	3 GHz to 30 GHz	Radar, microwave communications relay
Extra high frequencies (EHF)	1 to 0.1	30 GHz to 300 GHz	Satellite-to-earth communications

5800 MHz ± 75 MHz
22,125 MHz ± 125 MHz.

Some of the assigned uses of the specific frequency regions are also listed in Table 1. Due to the accelerated application of microwaves, the microwave spectrum is overcrowded. The use of additional frequency bands is increasing at a rapid rate each year.

The U.S. Department of Health, Education, and Welfare, through its Bureau of Radiological Health, has completed a partial inventory of microwave towers, broadcasting transmitters, and fixed radar by states and regions (*8*). They stated that in July 1969, the United States had 71,524 microwave towers utilizing 191, 517 separate frequencies. There were 16,272 broadcasting stations in the country. These included AM and FM radio and commercial and educational television. They reported that there were 2,897 fixed radar devices in operation. These radar devices only included those used for tracking, identification, communications, and related operations. The statistics excluded mobile airborne, water borne, and vehicular radar devices, as well as classified military communications installations. The demand for better communications is resulting in a 15 percent increase in the number of towers each year.

Microwave radiation has been extensively used in medical diathermy. It is estimated that there are 10 to 15 thousand microwave diathermy units in operation (*9*). The average domestic shipments of units is approximately 700. If one-half of these are used to replace old units, the increase in units in operation would be approximately 3 percent per year.

Microwave power for industrial applications is in its early stages. Industry is, however, predicting an exponential growth in the number of units in operation. Some of the existing industrial uses are listed in Table 2 (*9*).

Table 2. Some Industrial Uses of Microwave Heating

Wood Drying	Chicken Processing
Paper Drying	Pre-Cooked Bacon
Film Drying	Baking
Ink Drying	Plastic Curing
Potato-Chip Cooking	Sterilization

The fastest growing use of microwave radiation is in home microwave ovens. From available information, the number of microwave ovens was in the neighborhood of 50,000 units as of January 1970 (*9*). Most of these ovens operate at a frequency of 2450 MHz with a small number operating at 915 MHz. Based on the past statistical information and market predictions of manufacturers, estimated annual sales of home microwave ovens have been made and are presented in Table 3 (*9*).

Table 3. Estimated Annual Sales of Home Microwave Ovens (1965-1975)

Year	Home microwave oven sales
1965	4,000
1966	5,908
1967	8,720
1968	12,880
1969	19,040
1970	28,400
1971	41,520
1972	61,320
1973	92,000
1974	132,800
1975	200,000

Maximum Permissible Exposure Standards

Before 1950, only a small segment of the population, primarily civilian and military personnel involved in the operation of radar installations, were exposed to microwave radiation of significant amounts. The military, realizing the potential hazard of microwave radiation, began to study the effects during the 1950's. In 1957, the Air Force established a Tri-Service Ad Hoc Committee to study the hazards of microwave radiation in order to establish safe exposure levels. As a result of these studies, the committee recommended a maximum safe exposure level of 10 mW/cm^2 for all frequencies. The U.S. Air Force adopted this exposure level on May, 1958 and applied it to a frequency range of 300 to 30,000 MHz (*10*).

In November, 1966, the United States of American Standards Institute, USASI, (now the American National Standards Institute) established a standard of 10 mW/cm^2 as averaged over any possible 0.1 hour period (*11*). In this USASI standard an attempt was made to compensate for environmental conditions by stating that, "Under conditions of moderate to severe heat stress the guide number given should be appropriately reduced. Under conditions of intense cold, higher guide numbers may also be appropriate after careful consideration is given to the individual situation." This 10 mW/cm^2 standard set by the USASI can be considered the occupational and industrial exposure guide presently followed in the U.S. However, no specific standard exists in the U.S. for the exposure of the general population to microwave radiation.

Due to the increased use of electronic equipment which generates radiation and, therefore, the potential for exposure to large segments of the population, the Congress of the United States enacted the Radiation Control for Health and Safety Act (Public Law 90-602) in 1968 (*12*). This Act delegated the responsibility of developing standards for the emission of radiation from electronic products and the enforcement of these standards to the Bureau of Radiological Health in the Department of Health, Education, and Welfare. Since there is a lack of definitive research data on long-term, low level effects on humans, a standard for leakage from microwave ovens has been established below the 10 mW/cm^2 level. The maximum permissible leakage from an oven containing a 274 ml water load place in a 600 ml beaker at a distance of 5 centimeters from the oven has been established at 1 mW/cm^2 at the factory and 5 mW/cm^2 during the life of the oven.

It is interesting to compare the standards of different countries for continuous permissible exposure. The United States, United Kingdom, France, and West Germany have generally accepted a power density exposure level of 10 mW/cm^2. The U.S.S.R. and Poland specify a permissible level of 0.01 mW/cm^2, which is a factor of 1000 less than that accepted by the U. S. and other western countries. Czechoslovakia has proposed a level of 0.025 mW/cm^2 for an average working-day exposure. A summary of maximum permissible intensities is presented in Table 4.

The fact that there is a factor of 1000 between the accepted U. S. standard and the Eastern European standard results from the different basis for determining biological effects. The U. S. accepted standard is based upon the cooling capability of the body (thus, a thermal effect), whereas the standard of the U.S.S.R. and Poland are based upon the interaction of the microwave fields with the brain and central nervous system as measured

Table 4. Maximum Permissible Intensities

Institution or Country	Frequency MHz	Maximum Permissible Intensity in mW/cm^2	Remarks[a]
U.S. Standards Institute C95.1 -1966	all	10 $1 mW\ hr/cm^2$	For periods of 0.1 hours or more during any 0.1 hour period
U.S. Army and Air Force (1965)	all	10	Maximum permissible level for continuous exposure
		10 - 100	Limited occupancy exposure time $T_p = \frac{6000}{W^2}$
	all	Over 100	Denied occupancy
United Kingdom (1963)	30 - 30,000	10	Continuous daily exposure in case of pulsed waves, an average over the complete train of pulses
France (1965)	all	10	For 1 hour or longer Formula $-T_p = 6000/W^2$ for periods less than 1 hour
West Germany	all	10	No allowance made for time of exposure
U.S.S.R. (1958)	300 - 30,000	0.01 0.1 1	Whole working day 2 - 3 hours daily 15 - 20 minutes daily
Poland (1961	Over 300	0.01 0.1 1	Whole working day 2 - 3 hours daily 15 - 20 minutes daily
Czechoslovakia (1965)	Over 300	.025 .01	Continuous exposure Pulsed exposure

[a]T_p is the time of exposure in units of minutes
W is the power level in units of milliwatts/square centimeter

by neurological or behavior effects.

More accurate, well-defined experiments are needed before these disagreements in the standards for safe levels of microwave exposures can be resolved.

Biological Effects

Many studies have been made on the biological effects of microwave radiation. These effects are usually designated as thermal or nonthermal in nature. Thermal effects are those effects which result from heating of the biological material and can be duplicated by heating the material by conventional means. Nonthermal effects or specific effects are those effects which result from the interaction of the electromagnetic field with the biological material and cannot be produced by conventional heating techniques. The thermal effects are best understood and are summarized in Table 5 (*13*).

As can be seen from the information in Table 5, microwaves of frequencies greater than 10,000 MHz (short wavelengths) do not penetrate beyond the skin and cause only skin surface heating. Microwave radiation of frequencies less than 150 MHz (long wave-

Table 5. Thermal-Biological Effects of Microwaves (13)

Frequency, Mega Hertz	Wavelength, cm	Site of major tissue effects	Major biological effects
>10,000	<3	Skin	Skin surface acts as reflector or absorber with heating effects
10,000	3	Skin	Skin heating with sensation of warmth
10,000 to 3,300	3 to 10	Top layers of skin, lens of eye.	Lens of eye and testicles particularly susceptible
10,000 to 1,000	3 to 30	Lens of eye	Critical wavelength band for eye cataracts and testicular damage
1,200 to 150	25 to 200	Internal body organs	Damage to internal organs from overheating
<150	Above 200		Body is transparent to waves above 200 cm

lengths) penetrate the body with very little loss in energy. The most susceptible organs of the body to thermal effects for frequencies between 150 and 10,000 MHz are the testicles and the eyes. The testicles are extremely sensitive to elevations in temperature. Ely et al *(14)* performed a study on dogs, rabbits, and rats in order to determine the threshold for testicular damage. They determined that 10 mW/cm^2 was the threshold for testicular damage for indefinite exposure. The pathological damage found in the testes include a degeneration of the epithelium lining of the seminiferous tubules, and a sharp reduction in the number of maturing spermatocytes in the human. The reduction in testicular function due to the heating effect at 10 mW/cm^2 appears to be temporary and probably reversible.

The possibility of damage to the eye is a very serious aspect of microwave radiation. Cataracts have been produced in the eyes of experimental animals (*15*, *16-19*). Several investigators (*14*, *17-19*) have used the eyes of rabbits (due to their similarity with the eyes of humans) to establish thresholds for cata-

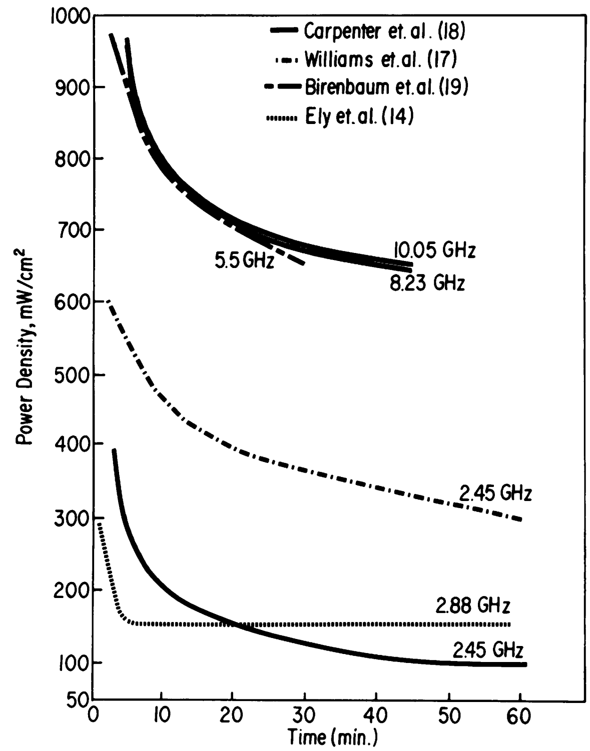

FIGURE 2. Power density and time thresholds for the induction of opacities in the eyes of rabbits.

Table 6. Neurological Effects

Subjective Effects on Persons working in Rf Fields (22)	Occurrence of Some Symptoms in Humans Exposed Professionally to High Frequency Electromagnetic Fields (750 KHz-200 MHz) (23)				
		Length of Employment			
		1–6 years (in average 4.3) (73 persons)		7–16 years (in average 9.6) (73 persons)	
Symptoms	Symptoms	percent of cases	number of cases	percent of cases	number of cases
1. Headaches	Headache	20.5	15	32.9	24
2. Eyestrain	Disturbance of sleep	13.7	10	23.3	17
3. Fatigue	Fatigue	12.3	9	17.8	13
4. Dizziness	General weakness	7.0	5	12.3	9
5. Disturbed sleep at night	Disturbance of memory	5.5	4	8.2	6
6. Sleepiness in daytime	Lowering of sexual potency	5.5	4	8.2	6
7. Moodiness	Drop in body weight	2.7	2	12.3	9
8. Irritability	Disturbance of equilibration	5.5	4	11.0	8
9. Unsociability	Neurological symptoms	0.0	0	15.1	11
10. Hypochondriac reactions	Changes in ECG	17.8	13	28.8	21
11. Feelings of fear					
12. Nervous tension					
13. Mental depression					
14. Memory impairment					
15. Pulling sensation in the scalp and brow					
16. Loss of hair					
17. Pain in muscles and heart region					
18. Breathing difficulties					
19. Increased perspiration of extremities					
20. Difficulty with sex life					

ract formation. These power-time thresholds are shown in Fig. 2 and are for exposure to continuous wave radiation. The data presented in Fig. 2 shows that the power-time thresholds are a strong function of the frequency of the radiation. The difference in the threshold levels presented for the same frequency is due to different criteria for designating initial onset of damage and different techniques for measuring the initiation of damage. Threshold levels for pulsed radiation and accumulative effects have not been adequately established.

Several cases of cataracts in man following accidental exposure have been reported. In 1952, Hirsch (*20*) reported the first case of cataract formation in a technician operating a microwave generator at a frequency range of 1500-3000 MHz. His eyes were exposed daily for approximately one year to an estimated power density of 100 mW/cm^2. Zaret (*21*) has reported three cases of cataracts in individuals who had histories of repeated microwave exposure. The estimated power levels were from 350 mW/cm^2 to several Watts/cm^2. The length of time between exposure to microwaves and opacity formation ranged from two months to many months depending on the power density of the radiation. From the limited information on human eyes, the threshold power-time curves of rabbits appear to be of the correct magnitude. However, until more information is obtained, the rabbit threshold curves should only be used as guides and not absolute values.

Non-thermal or specific effects, which result from exposure to low-level microwave radiation, are more difficult to detect than those mentioned above. This difficulty is due to the nature of the response of the biological specimen and the lack of explanation of the mechanisms causing the response. The first non-thermal effects to be considered will be neurological effects or effects on the brain and central nervous system. Marha (*22*) has listed the subjective complaints of persons working in radio frequency fields (Table 6). He lists many references from which he obtained this information. These references are from the Russian and Czechoslovakian literature and attempts to obtain copies of the articles have proved discouraging. Therefore, details such as the number of workers, the frequency, power level, type of radiation (continuous, pulsed or modulated), and duration of exposure are not known. Minecki (*23*) from the Institute of Occupational Medicine, Lodz, Poland has obtained results similar to those of Marha. Clinical observations of 146 persons occupationally exposed to microwaves ranging in frequency from 750 KHz to 200 MHz are presented in Table 6. The workers were divided into two groups depending upon the time of employment. The two groups were almost uniform with respect to age distribution. The frequency of the symptoms increased with time of exposure. In order to determine the exposure condition, radiation intensity measurements were made in all the working areas. The maximum values of intensity did not exceed 3 mW/cm^2 and the average values in different plants were not higher than 1 mW/cm^2. These levels are significantly lower than the accepted safe level of the U. S. of 10 mW/cm^2.

Letavet and Gordon (*25*) have reported clinical evidence of the effects of chronic low-power-density microwave radiation. The reported effects of chronic occupational exposure of the 525 microwave workers examined during the study are listed in Table 7. In addition to the above results, there was a high incidence of subjective complaints among the workers and these are also listed in Table 7. Statistical analysis of these findings are not reported in the studies.

Kholodov (*26*) has reported specific effects of microwaves on animals, Table 7. A large portion of his studies have been performed using rabbits as biological specimens. Both thermal and nonthermal power flux densities were used. For the low power density studies he used pulsed 2.5 GHz fields (λ= 12 cm) of 2 and 10 mW/cm^2 average power. The tests were conducted on 14 rabbits, which received a combined total of 300 exposures. Using EEG measurements, an increase in biopotential amplitude which was sometimes accompanied by a decrease in biopotential frequency was observed most frequently (76% of the total number of reactions). In 20 percent of the cases, a prolonged desynchronization reaction was observed.

Presman and Levitina (*24*) studied the nonthermal effects of microwaves on cardiac rhythm. The experiment was carried out on 8 male rabbits. Each animal was irradiated 12-13 times for 20 minutes at power levels of

Table 7. Neurological Effects

Clinical manifestations of chronic occupational exposure of humans to microwave radiation (25)

1. Bradycardia
2. Disruption of the endocrine-humoral process
3. Hypotension
4. Intensification of the activity of thyroid gland
5. Exhausting influences on the central nervous system
6. Decrease in sensitivity to smell
7. Increase in histamine content of the blood

Subjective Complaints

1. Increased fatigability
2. Periodic or constant headaches
3. Extreme irritability
4. Sleepiness during work

Effects of electromagnetic fields on the central nervous system of animals (26)

1. Changes in the conditioned reflexes
2. Alterations in sensitivity to light, sound, and olfactory stimuli
3. Changes in structure of skin receptors of the digestive and blood carrying system
4. Alteration in the biocurrents of the cerebral cortex
5. Reversible, structural changes in the cerebral cortex and diencephalon
6. Appearance of various vegetative reactions

7-12 mW/cm^2 and a frequency of 2500 MHz. Irradiation of the ventral side of the rabbits caused a decrease in the heart beat, and the irradiation of the dorsal side of the head and body increased the heart beat. The effect was attributed to central nervous system stimulation as a result of irradiation of the head, as contrasted to stimulation of peripheral receptors and the autonomic nervous system from ventral irradiations.

All the effects presented in Tables 6 and 7 are results of studies made in USSR or Eastern European counties. Clinical studies of microwave workers conducted in the United States by Daily (*27*) and Barron and Baraff (*28*), in contrast to the findings of Minecki (*23*) and Letavet and Gordon (*26*), indicated no acute, transient, or cumulative, physiological or pathological changes which could be attributed to microwave exposures. There have been, however, reported effects of low level microwave exposure on the central nervous system by U. S. and Canadian investigation. Frey (*4*) has found that the perception of sound can be induced in humans irradiated with modulated microwave radiation. Frey has also detected evoked electrical potential in the brain stem of cats as a result of irradiating with pulse-modulated UHF fields. Frey states that the effects are definitely present and that a description of the mechanism producing the effects are needed in order to evaluate the potential hazard. Hearn (*29*) has studied the effect of long continuous exposure of albino rats to low level RF fields. He looked at the effects on visual acuity and the frequency at which a flickering light appears to become steady. This flicker threshold is a sensitive well-established indicator of brain function. Hearn's results showed significant differences in the flicker thresholds of the irradiated as compared to the non-irradiated subjects. Korbel and Thompson (*30*) have found differences in behavior of rats exposed to low-intensity UHF radiations as compared to the unexposed. Tanner *et al.* (*31*) have exposed birds to very low power microwave fields. Marked changes in the behavior patterns were observed. The birds became hyperactive in their attempts to escape the field. The escape reaction manifested itself in either initiating flight, flanking (orienting body a certain way with the field), or collapsing. Infrared heating of the birds at very high levels did not evoke the behavior produced by the microwave fields.

Genetic effects have been produced by microwave fields. Van Ummersen (*32*) exposed chick embryos at the 48-hour stage of development to 2450 MHz CW radiation through the intact shell. The power density was of the order of 20 mW/cm^2 and the length of exposure was from 280 to 300 minutes. The temperature of the yolk was increased to 42.5°C; a rise of 3.5°C above normal incubator temperature. In general, the abnormalities appeared to be caused by the inhibition of growth and cell differentiation. Many embryos were only as large as 72-hour rather than 96-hour embryos. In many cases, further cell differentiation of the brain, eye, wing buds, and heart had been inhibited. Development of hind limbs, tail, and allantois was suppressed. To investigate whether the 3.5°C increase in temperature over the incubation temperature was the cause of the abnormalities, 41 fertile control eggs were incubated at a 42.5°C temperature level for the same length of time; the experimental eggs had been raised to 42.5°C by the microwave radiation. No abnormalities were found in the eggs which had been incubated at the elevated temperature of 42.5°C. Van Ummersen concluded that since the microwave radiation induced abnormal development of the chick embryos, while conventional heating to the same temperature did not cause abnormalities, some factors other than a thermal one produced the biological effect.

Carpenter *et al* (*33*), observing that microwaves appeared to inhibit cellular differentiation in the developing chick embryos, performed studies on pupae of the "mealworm" beetle (*Tenebrio molitor*). He exposed the pupae to microwaves of a frequency of 10,155 MHz at power densities of 80 mW/cm^2 and 20 mW/cm^2. The results of Carpenter's studies are presented in Table 8.

Table 8. Effect of 10,000-MHz Radiation on Tenebrio Molitor Pupae (*33*)[a]

	Period of Time in Wave-guide	Micro-wave Power in Wave-guide	Pupal Deaths	Grade 1 Anomaly	Grade 2 Anomaly	Grade 3 Anomaly	Normal Adults	Total
Untreated controls	None	None	7 (5.1)	6 (4.4)	2 (1.5)	0 (0)	122 (89)	137 (100)
Waveguide controls	20 min	None	0 (0)	0 (0)	1 (3.4)	0 (0)	14 (93)	15 (100)
	30 min	None	1 (3.4)	1 (3.4)	1 (3.4)	0 (0)	26 (89.6)	29 (100)
Irradiated pupae	20 min	80 mW	20 (25)	22 (27.5)	10 (12.5)	0 (11.9)	19 (23.7)	80 (100)
	30 min	80 mW	8 (22.9)	7 (20)	1 (2.8)	7 (20)	2 (34.3)	35 (100)
	120 min	20 mW	1 (4)	4 (16)	10 (40)	5 (20)	5 (20)	25 (100)

[a]Numbers in parentheses are percent figures

The different grades of abnormal development are as follows:

- Grade 1 anomaly — normal head and thorax, pupal abdomen with pupal case sometimes attached; wings and/or elytra (wing covers) absent, reduced, or shredded,
- Grade 2 anomaly — normal adult head, thorax, and abdomen, wings and/or elytra rumpled or shredded,
- Grade 3 anomaly — normal adult except for discrete holes in elytra.

At the exposure to 80 mW/cm^2 power density, the temperature rise in the pupa abdomen, as measured by a fine copper-constantan thermocouple, was 12.5°C. The temperature of twenty control pupae was increased by 12°C for 20 minutes by conventional heating. In these twenty controls, there were no deaths, 75 percent emerged normal, and 25 percent exhibited abnormalities. Another twenty control pupae were heated to a 3°C temperature rise (corresponds to 20 mW/cm^2 exposure) by conventional means. Of these twenty, 17 or 85 percent developed normally as opposed to only 24 percent for those exposed to microwaves and raised to the same temperature. From these studies, Carpenter *et al.* (*33*) conclude that the effect cannot be explained as a thermal effect, but rather a specific effect caused by the interaction of the microwave field and the biological specimen.

Other genetic effects have been reported. Heller and Teixera-Pinto (*34*) reported rf-induced chromosomal aberrations in garlic root tips at a frequency of 27 MHz. Janes *et al.* (*35*) reported microwave induced chromosomal effects in a study using chinese hamsters at a frequency of 2450 MHz. Mickey (*36*) observed two types of effects on Drosophila when exposed to pulsed UHF fields (5-40 MHz): pathological somatic changes, not hereditarily transmitted, and hereditarily transmitted changes in the germ cells. Heller *et al.* (*37*) showed that mutagenic effects similar to those of ionizing radiations could be produced in bacteria, spores of lower fungi and higher plants, and insects by exposure to pulsed electromagnetic fields. It is impossible to evaluate the effects listed in this paragraph in terms of thermal or nonthermal mechanisms due to the lack of measurements and controls on the experiments.

Only one statement on the possible genetic effects of microwave radiation on humans has been reported. Sigler *et al.* (*38*) reported that there was a higher incidence of Down's Syndrome in children whose fathers had prior occupational exposure to radar. The authors realize the questionable statistical validity of their study and only suggest the relationship between mongolism and paternal radar exposure.

Critical Review of the Literature

A critical review of the literature on the biological effects of microwave radiation immediately reveals the limitations and inadequacy of much of the work. In many cases this situation is not the fault of the investigators but rather is due to the many difficulties in quantitating experiments in this area of research. Accurate, quantitative experiments are difficult to achieve because the microwave field interacts with the detectors which are placed in the biological specimen. The presence of these detectors, usually thermocouple or thermistor probes, can cause hot spots in the biological material. Due to the complex nature of electromagnetic radiation, it is very difficult to evaluate the magnitudes of these extraneous effects. Extreme care must be taken in all studies in order to eliminate these artifacts. In general, the usefulness of much of the reported results has been minimized due to the unanswered questions concerning the work. Many of the investigations were performed without adequate measurements of the exposure and dosimetric parameters. Insufficient controls on the biological specimens were maintained during exposure. Few mechanisms of interaction of the specimen with the electromagnetic field were specified. Many of the described biological effects were not evaluated in terms of their hazard potential (that is to say, is the biological effect harmful to human health or to the environment in which he lives?).

The U.S.S.R., which has a safe exposure level 1000 times less than the U. S., has reported behavioral and neurological effects at very low power levels. As indicated in a previous section, many of the effects are subjective in nature (headaches, fatigue, etc). In many cases, the reports of the work used to support these effects do not specify the exact parameters and conditions of the experiments. Therefore, in the U.S. many of our scientists doubt the validity of the very low U.S.S.R. standard. It must be recognized, however, that the Russian scientists have placed much more emphasis and research effort into the study of the effects of electromagnetic radiation on the brain and central nervous system than the U.S. scientists. Since their safe level of exposure is based on these neurological and behavior effects, it is my opinion that we should not neglect the U.S.S.R. results until we have sufficient proof that the effects of microwaves on the brain and central nervous system are not detrimental to the health and well-being of our people.

Research Needs

Many questions remain to be answered before safe levels of microwave exposure can be specified. Some of the studies necessary to answer these questions have been stated (*39*) and will be reported here. The development of techniques and instrumentation for the determination of the exposure and dosimetric parameters should be emphasized so that quantitative research can result. Epidemiological and clinical investigations should be undertaken of groups of workers exposed to high and low levels of microwave radiation. In particular, behavorial and physiological effects should be investigated, especially as they may be related to functions of the central nervous system or to congenitally derived disorders. Studies on animals should be undertaken with particular emphasis on the detection of possible nonthermal and cumulative effects. Exposures to continuous, modulated, and pulsed fields should be performed. Frequency specific effects, influence of pulse repetition rate, peak power and average power density should be studied. Research is needed on the interaction of microwave radiation with tissues and cells in various organ and animal systems. Possible genetic and mutagenic effects of microwaves should also be explored. In all these studies, mechanisms of interaction of the microwave radiation and the biological system must be determined. The biological effect must also be interpreted in terms of its hazard potential to man and his environment.

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